RoboCupRescue 2006 – Robot League, Deutschland1 (Germany)

Kai Lingemann[1], Andreas Nüchter[1], Joachim Hertzberg[1], Oliver Wulf[2], Bernardo Wagner[2], Kai Pervölz[3], Hartmut Surmann[3], and T. Christaller[3]

[1] University of Osnabrück, Institute for Computer Science
Knowledge-Based Systems Research Group
Albrechtstraße 28, D-49069 Osnabrück, Germany
`<lastname>@informatik.uni-osnabrueck.de`
`http://www.uni-osnabrueck.de/kbs`

[2] University of Hannover, Institute for Systems Engineering (ISE/RTS)
Appelstraße 9A, D-30167 Hannover, Germany
`<lastname>@rts.uni-hannover.de`
`http://www.rts.uni-hannover.de/en`

[3] Fraunhofer Institute for Autonomous Intelligent Systems (AIS)
Schloss Birlinghoven, D-53754 Sankt Augustin, Germany
`<firstname>.<lastname>@ais.fraunhofer.de`
`http://www.ais.fraunhofer.de/index.en.html`

Abstract. After scoring second in RoboCup Rescue 2004 with Kurt3D and participating in 2005 with two robots, namely Kurt3D and RTS Crawler, we concentrated on the development of interaction between both vehicles. Kurt3D is able to autonomously explore and map the environment in 3D and search for victims. The RTS Crawler is designed to access more demanding territory (i.e., red arena), working either remote controlled or semi-autonomous. The key innovation of this system lies in the capability for autonomous 6D SLAM (simultaneous localization and mapping) and 3D map generation of natural scenes, combined with the intelligent cooperation between robots that enables one operator to efficiently map and explore the whole arena.
The robots are equipped with dedicated state of the art equipment, e.g., 3D laser range finders, infrared camera and CO_2-sensor. Robots as well as operator station are rather compact and easy to set up. The challenge of controlling two rescue robots with only one operator is managed with a redesigned user interface and a number of autonomous and semi-autonomous features.

Introduction

The team Deutschland1 is a cooperation between the University of Osnabrück, the University of Hannover and the Fraunhofer Institute for Autonomous Intelligent Systems and combines specific expertise from each of the three institutes.

Our approach to the rescue robot league competition is based on collaboration of two robots, one driving autonomously in easily accessible parts of the arena, the other one being manually steered through more demanding terrain. Both robots acquire 3D information of the environment and merge them into one global, consistent map. This procedure allows us to explore large parts of the arena, including map building, localization and victim identification, with one operator only, and is easily scalable for two or more autonomous robots.

The goal of our research is to have an affordable autonomous mobile robot system for indoor and outdoor environments that is able to generate 3D geometry maps of natural scenes from scratch. It should work completely autonomously, with no landmarks or beacons, not only on flat or horizontal floors. The motivation is the hypothesis that reliable and cheap 3D information would be badly needed for advancing robotics research as well as for advancing service robotics applications. We also assumed that getting the best possible sensor information about destroyed areas is the crucial point and that especially high quality distance measurements and a complete 3D model of the scene are most important.

1 Team Members and Their Contributions

Our team consists of the following members:

- Andreas Nüchter: 3D data processing and visualization, 6D SLAM
- Kai Lingemann: 2D localization, 3D data processing
- Kai Pervölz: Mechanical design, camera and servo control module
- Hartmut Surmann: Robot- and laser control software
- Oliver Wulf: 3D laser scanner, 3D data processing, robot design

Among other people that are involved in the preparations for RoboCup 2006, these people must be emphasized for their roles in the project:

- Thomas Christaller: Director of AIS, promoter of AIS's RoboCup midsize league team and initiator of the new RoboCup rescue project
- Joachim Hertzberg: Head of Knowledge-Based Systems group at University of Osnabrück, scientific advisor
- Bernado Wagner: Head of Real Time Systems group at University of Hannover, scientific advisor

2 Operator Station Set-up and Break-Down (10 minutes)

The whole operator system will be included in a box that allows the hardware to be carried to the operator station resp. disaster site. No time consuming putting together of hardware has to be done on site.

3 Communications

Wireless LAN in the 5 GHz range according to IEEE 802.11A specification is used for communicating with the robot. The power is limited to 50 mW. Special antennas can be used to ensure optimal transmission.

Rescue Robot League		
Team Deutschland1 (Germany)		
Frequency	**Chanel/Band**	**Power (mW)**
5.0 GHz – 802.11a	selectable	50

Table 1. Used communication frequencies.

4 Control Method and Human-Robot Interface

The human-robot interface (current version: Fig. 1) is designed to control 2 to n rescue robots with one operator. To do so the operator has got one operator station consisting of two laptops, one joystick, one wireless connection and a printer.

One laptop is used to provide a good overview of the situation. It displays a global 3D map of the explored area. This map includes obstacles and victims as well as the current positions of all robots. The operator can use the mouse or keyboard to make manual corrections of the map, add victim information and print out the final map. The second laptop is used to provide the local view of one selected rescue robot. This local view contains sensor information like camera images, thermal images, CO_2 readings, an artificial horizon and a local obstacle map. As there is only one laptop used for controlling n ($n \geq 2$) robots, the display can be switched between the different robots. In addition to the sensory display the second laptop is also used to send robot motion commands.

There are three different methods to control the robots motion: Direct, semi-autonomous and autonomous mode. As these three modes are in principle platform independent, the operator can control Kurt3D in the same way as the Crawler. By this means the required training of the operator is reduced and rapid switches between different robots are possible.

- In *direct mode* a joystick is used to drive the robot manually in difficult situations. Since the operator is part of the control loop, high frequent joystick and sensor updates are needed. Due to inherent latencies in video transmission with WLAN the maximum velocity of the robot is reduced.

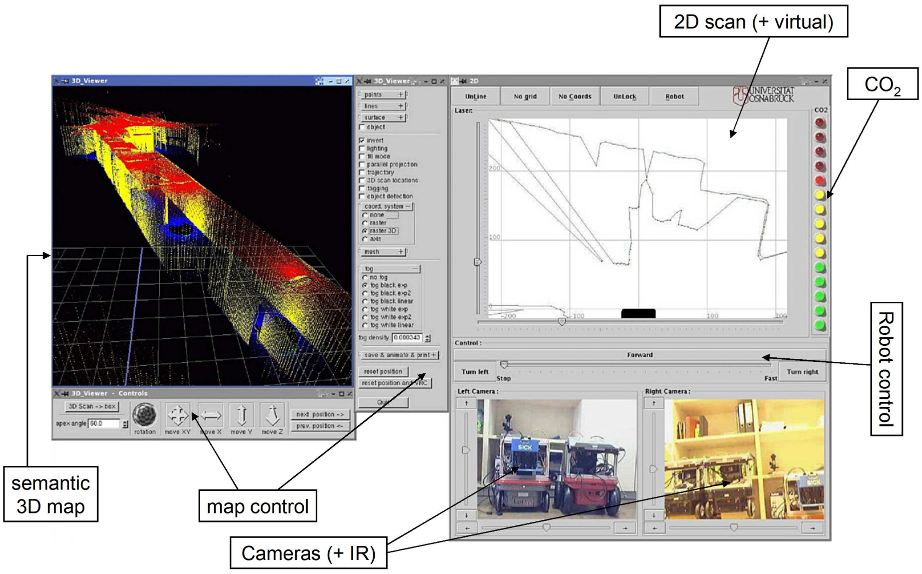

Fig. 1. The user interface for controlling the mobile robot Kurt3D. The left part shows the 3D map, with semantically labeled points (blue for floor points, yellow for wall points, red for ceiling points) and the OpenGL controls. The right part shows a local virtual 2D scan, two camera images and the measurement of the CO_2 sensor. The left camera image corresponds to the left pan and tilt camera, the right image can be switched between camera and IR camera.

- In the *semi-autonomous mode* the operator is commanding local target positions by clicking into the map. While the robot is moving autonomously to this position the operator can concentrate on victim identification or can give motion commands to other robots.
- The *autonomous mode* is designed to drive insight the yellow arena. As there is no interaction with the operator, the robot needs to explore the environment, do SLAM (mapping and localization) and victim identification autonomously. Due to the sensors requirements for autonomous victim identification this mode is currently available on Kurt3D only.

Kurt3D is constructed and equipped for autonomous application. This feature allows the exploration with both robots simultaneously, where the yellow part of the arena is mapped & searched for victims by Kurt3D, while terrain not accessible by the wheeled robot is explored by the teleoperated or semi-autonomous Crawler.

5 Map generation/printing

Our method of map generation builds essentially on the 3D laser scanner [13] as the key sensor, which is described in more detail in the subsequent section 6. In fact, SLAM (simultaneous localization and mapping) is done, so the separation between describing map generation and localization is only followed here to adhere to the given structure of this team description document. The distinctive feature of our maps is that they consist of true 3D data (laser scan points) and can be built in full autonomy [10].

For the purpose of sketching the mapping procedure in isolation, assume there is a 3D laser scanner that delivers as an output of one measurement a cloud of points representing 3D distance measurements over 360° at a resolution of 1°. The 3D map building works by a sequence of

1. 3D scanning the scene from the current pose
2. Registering the latest scan with the previous 3D map (initially empty)
3. Determining the next accessible best view pose to steer to
4. Navigating to this pose
5. Going back to item 1., unless some termination condition is fulfilled.

The complete process has been demonstrated to work on-line on a mobile robot in full autonomy [6], but the Kurt3D robot can also be operated under manual control in the view pose planning and navigation part. As an example, Fig. 2 shows a 3D map from last year's RoboCup Rescue competition.

The basic registration is a variant of the ICP algorithm [2], made efficient for use on-line on board the robot by reduction of the point clouds and efficient representation (approximate kD trees) of the remaining point set [10]. To further enhance both quality and speed of the matching, semantic information is utilized. Surface attributes are extracted and incorporated in a forest of search trees in order to associate the data, i.e., to establish correspondences. The basic idea of labeling 3D points with semantic information is to use the gradient between neighboring points to differ between three categories, i.e., floor, object and ceiling points [7]. Fig. 2 and 3 show 3D maps containing semantic information.

The accuracy of the maps is limited by two factors, first the accuracy of the laser scanner, and second any remaining registration errors. Based on the accuracy of the SICK scanner employed, each 3D point has a resolution of 5 cm within the measurement ranges involved here. Online registration may in principle induce errors derived from miscalculations in the prior scan pose estimations. (The registration method of simultaneous matching [10] that we have developed to generate very accurate 3D maps is relatively computation intensive and could not be used on-board a robot in the rescue competition.) We made only positive experiences with our on-line registration procedures in structured environments like the ones in the rescue arenas. Our work described in [1] gives some details about that.

One of the distinctive features of our registration approach is the fact that it works under translations in all three directions (x, y, z) and rotations in all

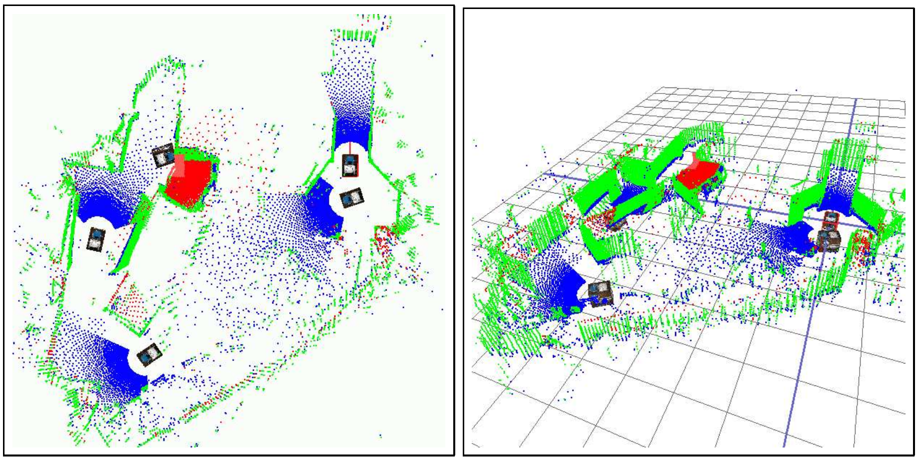

Fig. 2. 3D maps of the arena at RoboCup rescue 2005, Osaka. The scan points have been colored according to their semantic interpretation (blue: floor, red: ceiling, green: walls and other objects). The robot's position when taking 3D scans is indicated. Left: Top view. Right: View from slightly above. Grid cells designate an area of 1×1 m

three Euler angles (yaw, pitch and roll). The respective version of the simultaneous localization and mapping is named 6D SLAM, emphasizing the fact that, different to SLAM approaches that assume the robot to sit on a plane surface and considering poses only in terms of three mathematical dimensions (x, z, θ_y), we can cope with poses in the full range of six mathematical dimensions possible for a robot in 3D space. This is crucially important for 3D geometry mapping if elevation (e.g., ramps) is present for the robot or if the robot may pitch or roll over ramps or over debris lying on the floor, as is to be expected in RoboCup Rescue scenarios (cf. Fig. 2). A video featuring a round trip of Kurt3D in AIS' robotics lab is available at [11].

There is a possibility for a human operator to highlight or clip 3D volumes in the 3D maps, for example to mark the place of victims. Using OpenGL, the point-based maps, as well as different varieties of meshes generated from them, are rendered and drawn on the screen from arbitrary perspectives. The user may navigate through the 3D scenes by way of a simple cursor control or a joystick control. Of course, arbitrary 2D views of the 3D maps may be printed as shown in Fig. 1 and 2.

6 Sensors for Navigation and Localization

As remarked in the previous section, the main sensor for navigation and localization is the 3D laser scanner. As there is still no commercial 3D laser range finder available that could be used for mobile robots, it is common practice to assemble 3D sensors out of a standard 2D scanner and additional motor drives [3, 9, 13]. The used scanner is based on a SICK LMS 220 in combination

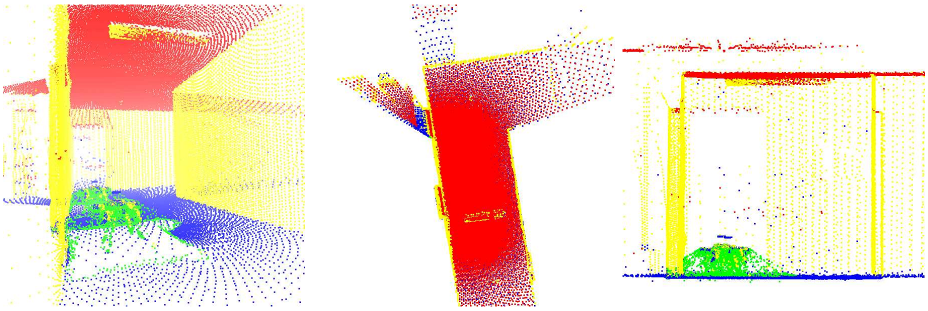

Fig. 3. Semantically labeled 3D point cloud from a single 360° 3D scan in an indoor office environment. Red points mark the ceiling, yellow points objects, blue points the floor and green points correspond to artefacts from scanning the RTS/ScanDrive and the robot.

with the RTS/ScanDrive developed at the University of Hannover. Different orientations of the 2D scanner in combination with different turning axes result in a number of possible scanning patterns. The scanning pattern that is most suitable for this rescue application is the yawing scan with a vertical 2D raw scan and rotation around the upright axis (see Fig. 4, middle).

The yawing scan pattern results in the maximal possible field of view (360° horizontally and 180° vertically) and a uniform radial distribution of scan points. As 3D laser scanner for autonomous search and rescue applications needs fast and accurate data acquisition in combination with low power consumption, the RTS/ScanDrive incorporates a number of improvements. One mechanical improvement is the ability to turn continuously, which is implemented by using slip rings for power and data connection to the 2D scanner. This leads to a homogeneous distribution of scan points and saves the energy and time that is needed for acceleration and deceleration of panning scanners. Another improvement that becomes more important with short scanning times of a few seconds is the compensation of systematic measurement errors. In this case the compensation is done by sensor analysis and hard realtime synchronization, using a Linux/RTAI operation system. These optimizations lead to scan times as short as 3.2 s for a yawing scan with 1.5° horizontal and 1° vertical resolution (240×181 points). For details on the RTS/ScanDrive see [13].

The registration and map building based on the 3D scanner data is described in the previous section. The registration process needs as input an estimation of the robot pose (in 6D for 6D SLAM) for the recent scan relative to the pose of the previous or some other earlier scan. This prior pose estimation is based on wheel encoder based odometry for x, y, and z values. We have some experience with tilt sensors for the pitch and roll angles as well as with gyros on the basic platform KURT2 [8], which can be used for estimating the three Euler angles. For estimating the 6D pose the scan registration matrix is used that represents all degrees of freedom. The x, y, and z values are propagated in 6D by multiplying the resulting simplified matrix with the inverse of the full registration matrix of the previous scan. This updated pose is then used as the basis for the pose tracking process up to the stop at the next scan pose.

Compared to previous work [5], the main innovation is the intelligent use of the 360 degree scanner as described above, as well as the robot cooperation for map building and localization (cf. Sec. 11). Experiences with the former tilting scanner showed that in RoboCup Rescue applications, due to the specific environment the overlap of two consecutive scans was sometimes too low so that the operator had to intervene in the matching process. The new scanner reduced this problem, since it provides backward vision, as proven in RoboCup 2005. In the improved system, a planning algorithm will guide the robot (when driving autonomously) resp. the operator not only to the next best pose for exploration, but will also monitor the sensed environment information, deciding on when a new 3D scan has to be acquired and matched into the existing map (SPLAM – Simultaneous Planning, Localization And Mapping). The following procedure is based on the horizontal 2D laser scans, taken while the robot is driving:

1. Transform the first 2D scan with the corresponding robot pose and create a polygon from the data by connecting neighboring points. Set it as reference scan.
2. Transform the next scan with the current robot pose and and build a polygon, too. Use a polygon clipping algorithm to to calculate the intersection of the polygons.
3. Calculate the area A_R of the reference polygon, the area A_C of current polygon and the area A_I of result of the intersection polygon. Suggest to the operator to acquire a new 3D scan, iff $\min(A_I/A_R, A_I/A_C)$ falls below a threshold (here 0.5).
4. If a new 3D scan is acquired, set the corresponding 2D scan the new reference scan.

Uncertainties of the robot pose are handled implicitly by the algorithms, i.e., as the robot pose gets inaccurate, the overlap of the scans reduces and 3D scans are acquired to correct the robot pose.

For means of situation awareness and path planning, virtual 2D scans are used, based on the 3D information acquired with the rotating scanner constantly while driving [12]. Objects that are preferably used for situation awareness of the operator are walls and obstacle points. The first step to create these virtual 2D scan is to project all 3D points onto the plane by setting the height coordinate to zero. A virtual 2D scan that contains primarily walls can thereafter be assembled by taking one point out of each vertical raw scan. This point is chosen to be the one with the largest distance to the center of the robot. These points represent the outer contour in Fig. 1 (right).

For autonomous control, virtual points are used that are obtained in the same manner, but taking into account the data point nearest to the scanner, restricted to an area according to the size of the robot. These scans are considerably better than ordinary 2D scans, too, since due to the absence of a fixed 2D horizontal scan plane, 3D objects with jutting out edges are correctly detected as obstacles. Nevertheless one has to think carefully about the distinction between

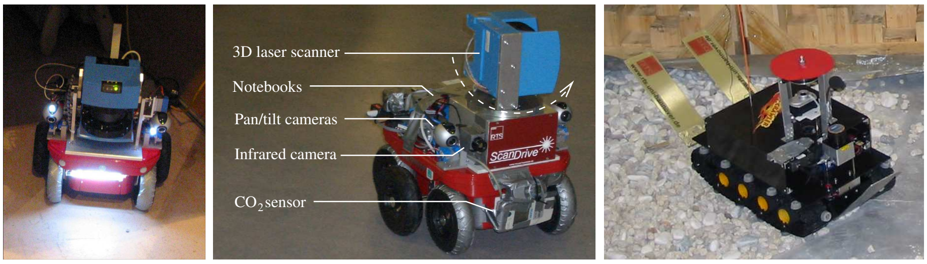

Fig. 4. Left: The Kurt3D robot as used at RoboCup Rescue 2004 in Lisbon, equipped with a tiltable scanner. Middle: Current Kurt3D robot with RTS ScanDrive. The 3D laser range finder rotates constantly around a vertical axis. Right: RTS Crawler.

solid obstacles just like walls, and movable objects like crumpled newspapers or curtains that may appear as obstacles in a virtual 2D scan.

7 Robot Locomotion

The Robot Platform Kurt3D. The Kurt3D outdoor edition (Fig. 4, left, middle) as used in the RoboCup rescue league competition is a mobile robot platform with a size of 45 cm (length) × 33 cm (width) × 26 cm (height) and a weight of 15.6 kg. Two high power 90 W motors (short-term 200 W) are used to power the 6 wheels. Although being wheel-driven, the robot is steered using the differential drive model, which is primarily known from skid-steered vehicles. Compared to the original Kurt3D robot platform, the outdoor version has larger wheels, where the middle ones are shifted outwards. Front and rear wheels have no tread pattern to enhance rotating. Kurt3D operates for about 4 hours with one battery charge (28 NiMH cells, capacity: 4500 mAh) charge. The core of the robot is a laptop computer running a Linux operating system. An embedded 16-Bit CMOS microcontroller is used to process commands to the motor. A CAN interface connects the laptop with the microcontroller.

The Robot Platform RTS Crawler. In order to drive and locate victims in terrain that is not accessible by the wheeled robot, we developed a tracked robot platform to cooperate with Kurt3D.

The RTS Crawler (Fig. 4, right) is a high mobility platform with a size of 40 cm (length) x 26 cm (width) and a total weight of 7 kg including sensors and CPU. The GRP chains are driven by two 60 W DC-Motors. Special rubber knobs give grip on rubble and uneven ground. The crawler is operated either via a 40 MHz remote control or with the onboard embedded PC. To ease remote operation with a delayed feedback speed controller for each chain is implemented. The platform is equipped with a number of sensors. The sensor most useful for human operation is a CCD camera pointing to an omnidirectional mirror.

The image of this omnidirectional camera is distorted and has a relatively low resolution. On the other hand, it gives a good overview of the robot situation and the whole environment. This allows robot operation without camera panning. The 2D laser range sensor Hokuyo URG is used to measure distances to obstacles in the robot vicinity. Thereby it is possible to cope with narrow passages. The scanner is mounted on a tiltable unit to acquire 3D information to contribute to Kurt3D's map building process. To navigate safely in uneven terrain and to reduce the risk of flipping over, the robot state is measured with a 3 DOF gyro. All sensor data is captured with an on-board embedded PC and transferred via WLAN to the remote operation terminal.

8 Sensors for Victim Identification

Autonomous victim detection is currently mainly based on infrared camera data. While driving, the robot is scanning the environment for heat sources with a temperature similar to human bodies. When such a heat source is detected, the robot drives autonomously into its direction, stops 80 cm in front of it and informs the operator. Furthermore, victims are identified based on the camera images by detecting motion and skin like colors. A microphone is used to detect human voices, passive infrared sensors around the robot's chassis help localize thermal sources, and one carbon dioxide sensor helps verify the vital signs of the victims.

9 Other Mechanisms

The first key innovation of our system lies in the capability for autonomous or operator-assisted 6D SLAM and 3D map generation, as explained in Sec. 5 and 6. The second is the cooperation between one remote controlled or semi-autonomously driving robot and one or more autonomous robots.

10 Team Training for Operation (Human Factors)

There is no special training necessary for the operator. Both robots can be steered by a self-explaining user interface or via joystick. Fig. 1 shows the current version of the GUI, which is currently under reconstruction.

11 Application to Real Disaster Site

We have until now no practical experiences with our system on a real disaster site. A priori, we think that both the integrated system (Kurt3D robot) and the 3D map construction equipment alone (3D scanner plus scanning, registration, rendering and interpretation software) would be robust enough for standing a field test. We are willing to submit our system to such a test. The robustness of our system was shown in the last two year's competitions; in Lisbon we scored second.

As a surrogate for disaster sites and in order to evaluate the quality and robustness of algorithms and hardware, we have made extensive experiments in an outdoor environment [4].

Nevertheless, the Kurt3D robot has some obvious physical and geometrical limitations that are acceptable for the competition, but would have to be respected in a field test. For example, it is a relatively small, wheeled platform with restricted ground clearance. Therefore we developed the tracked robot platform RTS Crawler to actively cooperate with Kurt3D, for building a joint 3D map of the environment.

12 System Costs

The total cost of one robot, including some necessary minor parts that are not shown in the table, is about 38.000 €. For the operator station a robust laptop PC with joystick and wireless LAN interface is recommended, which costs about 4.000 €. Further details about the system are given at [3].

TOTAL SYSTEM COST:	38.348 €
KEY PART NAME:	KURT2 robot platform
MANUFACTURER:	KTO
COST:	9.450 €
WEBSITE:	`http://www.kurt2.de/`
DESCRIPTION/TIPS:	The one mobile robot platform.
KEY PART NAME:	On-board laptop
MANUFACTURER:	Panasonic CF-73
COST:	4.000 €
WEBSITE:	`http://www.panasonic.com`
DESCRIPTION/TIPS:	The control laptop, acquire and send sensor data, handle operator commands.
KEY PART NAME:	3D Laser Scanner
MANUFACTURER:	SICK + RTS Hannover
COST:	10.000 €
WEBSITE:	`http://www.rts.uni-hannover.de`
DESCRIPTION/TIPS:	Used to take 3D scans ;-)
KEY PART NAME:	Cameras with pan-tilt module
MANUFACTURER:	Logitech + Fraunhofer Institute AIS (pan-tilt)
COST:	2×499 €
DESCRIPTION/TIPS:	Standard USB webcams on pan tilt module.
KEY PART NAME:	Infrared camera

MANUFACTURER:	Flir Sstems / Indigo
COST:	8.900 €
DESCRIPTION/TIPS:	IEEE1394 IR camera (A10)

KEY PART NAME:	RTS Crawler
MANUFACTURER:	RTS Hannover
COST:	5.000 €
DESCRIPTION/TIPS:	Platform, as described above.

References

1. K. Lingemann A. Nüchter, H. Surmann and J. Hertzberg. 6D SLAM - Preliminary Report on closing the loop in Six Dimensions. In *Proc. of the 5th IFAC Symposium on Intelligent Autonomous Vehicles*, June 2004.
2. P. Besl and N. McKay. A method for Registration of 3–D Shapes. *Journal of the IEEE Transactions on Pattern Analysis and Machine Intelligence (TPAMI '92)*, 14(2):239–256, February 1992.
3. Kurt3D description. `http://www.ais.fraunhofer.de/ARC/Kurt3D/`, 2005.
4. A. Nüchter, K. Lingemann, J. Hertzberg, and H. Surmann. Heuristic-Based Laser Scan Matching for Outdoor 6D SLAM. In *KI 2005: Advances in Artificial Intelligence. 28th Annual German Conference on AI*, Koblenz, Germany, 2005.
5. A. Nüchter, K. Lingemann, J. Hertzberg, H. Surmann, K. Pervölz, M. Hennig, K. R. Tiruchinapalli, R. Worst, and T. Christaller. Mapping of Rescue Environments with Kurt3D. In *Journal of the IEEE International Workshop on Safety, Securety and Rescue Robotics*, Kobe, Japan, 2005.
6. A. Nüchter, H. Surmann, and J. Hertzberg. Planning Robot Motion for 3D Digitalization of Indoor Environments. In *Proceedings of the 11th IEEE International Conference on Advanced Robotics (ICAR '03)*, pages 222–227, Coimbra, Portugal, June 2003.
7. A. Nüchter, O. Wulf, K. Lingemann, J. Hertzberg, B. Wagner, and H. Surmann. 3D Mapping with Semantic Knowledge. In *Proceedings of the RoboCup International Symposium*, Osaka, Japan, July 2005.
8. E. Solda, R. Worst, and J. Hertzberg. Poor-Man's Gyro-Based Localization. In *Proceedings of the 5th IFAC Symposium on Intelligent Autonomous Vehicles (IAV '04)*, Lisbon, Portugal, June 2004.
9. H. Surmann, K. Lingemann, A. Nüchter, and J. Hertzberg. A 3D laser range finder for autonomous mobile robots. In *Proceedings of the 32nd International Symposium on Robotics*, Seoul, Korea, 2001.
10. H. Surmann, A. Nüchter, and J. Hertzberg. An autonomous mobile robot with a 3D laser range finder for 3D exploration and digitalization of indoor environments. *Robotics and Autonomous Systems*, 45(3-4):181–198, December 2003.
11. 6D SLAM video. `http://www.ais.fraunhofer.de/ARC/3D/6D`, 2005.
12. O. Wulf, K. O. Arras, H. I. Christensen, and B. A. Wagner. 2D Mapping of Cluttered Indoor Environments by Means of 3D Perception. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '04)*, pages 4204 – 4209, New Orleans, USA, April 2004.
13. O. Wulf and B. A. Wagner. Fast 3D Scanning Methods for Laser Measurement Systems. In *Proceedings of the International Conference on Control Systems (CSCS 2003)*, Bucharest, Romania, July 2003.